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Investigation of external triggering of substorms with Polar ultraviolet imager observations

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[1] The triggering mechanism(s) for the substorm expansion phase onset is one of the outstanding issues in magnetospheric physics. Previous studies have shown that an impingement of the high solar wind dynamic pressure may lead to the expansion phase onset of a substorm. These previous studies typically used a negative magnetic bay as the main proxy for a substorm, but we now know that some magnetic bays are associated not with substorms but with the enhancement of convection. Therefore it is reasonable to cast doubts on the compression trigger mechanism. In this study we use classical substorm onsets, "auroral breakups," which are the most reliable substorm onset indicator when identified with global auroral images, to reinvestigate this issue. We examine 43 interplanetary shock events that occurred between 1996 and 1999 with simultaneous global auroral images from the Polar ultraviolet imager images and the auroral electrojet indices. It is found, indeed, that ~52% of the shocks produce magnetic bays ($AL < -100$ nT). While most of the shocks enhance auroral luminosities, only 4 events (~9%) appear to have an auroral breakup preceded by an SSC/SI by 20 min (two events by 10 min). These results strongly indicate interplanetary shocks can produce negative magnetic bays but not auroral breakups (thus christened "compression bays"). An examination of precisely timed interplanetary magnetic field (IMF) during 11 substorms that occurred near the shock-induced SSCs/SIs indicates that northward turnings of IMF occurred more than 50% of time. Given such a low probability, it is concluded that shock compression is not likely to trigger substorms but enhances magnetospheric currents and auroral particle precipitation. In line with many previous study results, on the other hand, the northward turnings of IMF can be a plausible substorm triggering mechanism. *INDEX TERMS:* 2788 Magnetospheric Physics: Storms and substorms; 2784 Magnetospheric Physics: Solar wind/magnetosphere interactions; 2407 Ionosphere: Auroral ionosphere (2704); 2139 Interplanetary Physics: Interplanetary shocks; 2134 Interplanetary Physics: Interplanetary magnetic fields; *KEYWORDS:* substorm onset, substorm trigger, interplanetary shocks, northward IMF turnings

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1. Introduction

[2] Whether or not substorms can be triggered externally by discontinuities or variations in the solar wind plasma and interplanetary magnetic field (IMF) remains an outstanding question in magnetospheric physics. Discontinuities in the solar wind plasma such as shocks have long been considered as causes of magnetospheric substorms. It was first noted by *Heppner* [1955], before the term "substorm" was first invented [*Akasofu*, 1964], that negative magnetic bays, now known as one of typical substorm signatures, can occur during compression of the magnetosphere by shock impingement. Later, a number of detailed studies showed evidence of substorm triggers by storm sudden commencements (SSCs) or sudden impulses (SIs) produced by solar wind shocks [*Schieldge and Siscoe*, 1970; *Kawasaki et al.*, 1971; *Burch*, 1972; *Kokubun et al.*, 1977].

[3] The interaction between solar wind dynamic pressure pulses and the Earth's magnetosphere introduces a different

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type of coupling mechanism from the well-known magnetic field merging on the dayside magnetopause [*Dungey*, 1961]. When the high solar wind ram pressure acts on the magnetosphere, it first compresses the dayside magnetosphere earthward and causes eastward magnetopause currents to increase to balance the shock compressional force. This in turn produces a sharp positive excursion in the *H*-component of the ground magnetic field at middle and low latitudes called an SI or an SSC if a geomagnetic storm follows. As the high-pressure solar wind in the shock downstream moves tailward, the lobe magnetic fields become more stretched and the magnetic pressure increases, thus enhancing the cross-tail currents and causing the plasma sheet to thin. If the magnetic field becomes very stretched such that ion motion becomes nonadiabatic, magnetic reconnection will be initiated and a substorm can be triggered if the rate of reconnection grows explosively [*Coroniti*, 1985]. It is also possible that the cross-tail current enhancement may disrupt due to plasma current instabilities and ultimately lead to the formation of a substorm current wedge [e.g., *Lui et al.*, 1991, and references therein]. While this scenario of the substorm triggering mechanism by shocks appears plausible, controversy still exists because not all shocks produce substorms.

[4] The majority of previous studies of shock triggering of substorms has relied on ground magnetometer observations at high latitudes. However, it is not clear whether all negative magnetic bays result from the same source mechanism that leads to substorms. It is conceivable that any mechanism that can lead to enhancement of the auroral electrojets can also have similar effects on the ground magnetic field, such as convection bays [*Sergeev et al.*, 1998]. This possibility casts some doubt about previous study results. *Zhou and Tsurutani* [2001], to prevent ambiguity in using *AE* as a substorm proxy, recently reinvestigated this issue with global auroral images from the Polar ultraviolet imager (UVI). They studied 18 selected shock events that occurred in 1997 and 1998, during which UVI data are available, and concluded that substorm expansion phase onsets were observed 44% of the time, if the magnetosphere is "preconditioned" by a negative IMF for more than 1.5 hours. Because their substorm events consist of auroral intensification, not specifically substorm, their study results do not address the question concerning shock triggering of substorms.

[5] Another possible onset trigger is related to changes in the interplanetary magnetic field (IMF). Variations in the IMF have long been considered as a possible external trigger agent. These include a northward turning [e.g., *Burch*, 1972; *Caan et al.*, 1975; *Rostoker*, 1983; *Samson and Yeung*, 1986; *Lui*, 1996; *Lyons et al.*, 1997], a southward turning [*Tsurutani and Meng*, 1972], a reduction in the magnitude of IMF B_y [*Troshichev et al.*, 1986], and a sign change in IMF B_y [*Bae et al.*, 2001]. *Lyons* [1995] proposed a triggering mechanism for the northward turnings of IMF. He proposed that a reduction in the magnetospheric convection electric field creates an azimuthal pressure gradient that drives the substorm current wedge. Either a northward turning of the IMF or a reduction in $|B_y|$ will reduce convection and hence, according to this theory, trigger a substorm.

[6] Although some substorms are associated with turnings of IMF B_z, evidence exists indicating that some substorms are not. Substorms have been observed during very quiet intervals of southward IMF in the forms of magnetic bays [*Horwitz*, 1985] and auroral breakups [*Henderson et al.*, 1996]. A statistical study of the frequency of occurrence of negative magnetic bay triggers conducted by *McPherron et al.* [1986] indicated that some (44%) sharp bays are associated with either a northward turning or a fluctuation in the IMF B_z and some (30%) with a steady southward IMF component. This work seems to suggest that there are two types of substorms, one being externally triggered and one being spontaneous. However, *Lyons* [1996] argued that the substorm expansion onset is a response to external changes. In support of this view he pointed out that previous reports of onsets during steady IMF B_z did not use sufficiently accurate indicators of substorm onset, or that they ignored possible triggers such as IMF B_y, or that the events were not substorms, or that the IMF are improperly timed because of orientation and propagation of the IMF discontinuities in the solar wind.

[7] There are always uncertainties associated with onset identification. It is shown recently that the use of global auroral images to determine substorm onsets has advantages over many other substorm onset indicators, such as high-latitude magnetic bays, low-latitude Pi2 pulsations, auroral kilometric radiation (AKR), and dispersionless particle injections and magnetic field dipolarization at geosynchronous orbits [*Liou et al.*, 1999, 2000a, 2000b, 2001, 2002a]. All commonly used substorm onset identifiers typically, except perhaps AKR which is also measured by remote sensing techniques, lag behind the auroral breakup by a few minutes. These delays are not unexpected because substorms are a temporal and spatial phenomenon; substorm onsets determined from any in situ observation are subject to delays. Sometimes onset timing differences can be more than 10 min. Furthermore, these onset signatures may occur during nonsubstorm times (i.e., those not associated with auroral breakup), which is probably the most important source of uncertainty.

[8] Improperly timed IMF change at the magnetopause is probably the most obvious source of errors [*Lyons*, 1996]. Uncertainties associated with IMF timing probably outweighs uncertainties associated with imprecise onset timing. *Horwitz* [1985] used a nominal 1-hour for the time delay at ISEE 3. *Henderson et al.* [1996] shifted the IMF based on solar wind plasma parameters but without considering the structure of the IMF at IMP 8. *Lyons* [1996] assumed a Parker spiral IMF in the GSM *x-y* plane, uniform in the *z*-direction, convecting to the magnetopause at the measured solar wind velocity, and making contact with the magnetopause at $x = 10\ R_E$ and $y = 0$. The slowing of the solar wind as it crosses the bow shock was neglected. We know the IMF is not always in the Parker spiral form and the magnetopause location is not fixed in space. These types of assumptions are inadequate and can add significant uncertainties, at least as much as 10–20 min [*Ridley*, 2000].

[9] To settle this dispute, improvements in the data analysis techniques are essential. In this study we use auroral breakups identified from global auroral images as substorm indicators. Propagation of solar wind plasma and IMF data from a satellite location to the magnetosphere will be carried out by matching an IP shock with an SSC/SI. Using the property of good one-to-one correspondence

Table 1. Interplanetary Shock Events Identified With Data From SSCs/SIs and Wind Observations[a]

Date	Wind, UT	UVI, UT	SSC/SI, UT	AL_{min}, nT	Breakup, UT	IMF Type	Event Type
28 July 1996	1215		1307	NA		PN	NA
10 Jan 1997	0052	0104	0104	−24		PP	Q
09 Feb 1997	1250		1321	−218	1326	NN	T
01 May 1997	1203	1243	1241	−145	1244	NP	T
26 May 1997	0901		0957	−37		NP	Q
19 June 1997	0013		0032	−18		NN	Q
22 June 1997	0246		0314	−61		NN	Q
03 Aug 1997	1005		1040	−578	1032	NN	T
02 Sep 1997	2237		2259	−46		PP	Q
01 Oct 1997	0056	0100	0059	−185		PN	F
10 Oct 1997	1558	1616	1612	−77		NP	Q
23 Oct 1997	0809	0808	0804	−22		PP	Q
01 Nov 1997	0614	0636	0635	−89		PP	Q
06 Nov 1997	2220		2248	−275		NP	F
22 Nov 1997	0910	0950	0949	−363		NN	F
10 Dec 1997	0430	0525	0526	−153		PN	F
30 Dec 1997	0113		0209	−25		NN	Q
06 Jan 1998	1330		1416	−67		PN	Q
08 Jan 1998	0727	0836	0831	−28		PP	Q
31 Jan 1998	1554		1642	−146		NN	F
07 April 1998	1654		1750	−201		NN	F
03 May 1998	1701	1745	1743	−136		NN	F
08 May 1998	0923		0951	−406		PP	F
29 May 1998	1510	1539	1536	−700		PN	F
13 June 1998	1920		1926	−9		PP	Q
25 June 1998	1610		1636	−28		PP	Q
06 Aug 1998	0715		0736	−657		NN	F
10 Aug 1998	0030	0045	0046	−132		PN	F
08 Sep 1998	1743	1753	1748	−111		NN	F
24 Sep 1998	2320	2345	2345	−1670		NP	F
02 Oct 1998	0706	0724	0725	−299		PP	F
06 Oct 1998	1547		1630	−58		PP	Q
13 Nov 1998	0137		0142	−188	0156	NN	T
30 Nov 1998	0507	0508	0507	−201		NN	F
10 Mar 1999	0132		0130	−424		NN	F
05 May 1999	1541		1543	−111		PP	F
15 June 1999	1200		1308	−55		PP	Q
26 June 1999	0231		0325	−36		PN	Q
26 June 1999	1930		2016	−41		PP	Q
09 Sep 1999	1257[a]		1257	−36		PP	Q
22 Sep 1999	1210		1222	−697		NP	F
28 Oct 1999	1213		1215	−50		PP	Q

[a]From IMP-8 observations NN: Southward IMF before and after an SSC. PP: Northward IMF before and after an SSC. NP: Southward (northward) IMF before (after) an SSC. PN: Northward (southward) IMF before (after) an SSC. Q: Quiescent events. F: False positive events. T: Potential trigger events.

between IP shocks and SSCs/SIs for propagation provides much reliable IMF at onsets. Based on this method, errors associated with IMF propagation are expected to be minimized to within ~1 min [*Nishida*, 1978]. The rest of the paper is organized as follows. Observations and data analysis are given in section 2. A discussion is given in section 3, followed by the result summary and conclusions in section 4.

2. Observations

[10] This study started with a list of 103 SSC/SI events obtained from the National Geographical Data Center (NGDC) ftp server (available at ftp.ngdc.noaa.gov/STP/SOLAR_DATA). These events occurred between 1996 and 1999. We then searched solar wind plasma and magnetic field data from the Wind Solar Wind Experiment (SWE) [*Ogilvie et al.*, 1995] and the Magnetic Field Investigation (MFI) [*Lepping et al.*, 1995] for corresponding shock events. The shock times were determined with 3-s magnetic field data by using a standard step-function fit. The next step was to check the availability of UVI images. Events either without a clear IP shock association or without concurrent auroral observations are thrown out. Based on these selection rules, we have compiled a total of 43 events shown in Table 1 for a further study.

[11] The first two columns of Table 1 show the date and the UT time, respectively, of each event of shocks observed by Wind. Upon the magnetospheric compression by shocks, dayside auroral transients may appear as observed by UVI [*Zhou and Tsurutani*, 1999]. The onset time of the dayside transients, listed in the third column of Table 1, can sometimes be used to time the shock impingement. However, an SSC/SI (listed in the fourth column) should provide more reliable timing for the arrival of a shock at the magnetosphere, with an uncertainty of ~1 min [*Nishida*, 1978], because the small field of view and the low sensitivity of UVI often cause the dayside auroral brightening either not available or to delay. Details of the rest of the table columns will be given in the relevant sections.

[12] Although auroral breakups are the primary onset indicator used in the present study, we also considered negative magnetic bays by examining the westward auroral electrojet *AL* index. The criterion for a negative magnetic bay in association with an SSC/SI is that there must be a sharp decrease in *AL* by a minimum of 100 nT occurring within a 20-min window starting at the SSC/SI and the minimum must be observed within 30 min of the SSC/SI. As we can see from the fifth column of Table 1, 22 out of 43 events (52%) show a negative magnetic bay association, agreeing with previous results [e.g., *Kawasaki et al.*, 1971; *Kokubun et al.*, 1977]. Note that the choice of the bay criterion is somewhat arbitrary, because a quantitative definition for the substorm bay does not exist. A larger time window and a smaller value for the *AL* minimum eventually increases the bay occurrence rate.

[13] Global auroral images from the Polar ultraviolet imager (UVI) [*Torr et al.*, 1995] on board the Polar Satellite are used to determine auroral breakups. The Polar UVI produces an image of 200-by-228 pixels every 37 s. With a circular field of view of 8°, typical spatial resolution provided by the Polar UVI is about 30–40 km at an assumed 120-km emission height for images taken near the apogee of $\sim$9 R_E. However, images are constantly smeared by $\sim$10 pixels by wobble of the satellite that reduces the spatial resolution accordingly in the wobble direction.

[14] In this study auroral breakups are identified visually from a sequence of processed images. Identification of auroral breakups from a sequence of global auroral images takes some experience, since nonsubstorm geomagnetic disturbances can also lead to auroral brightenings. For example, auroral brightenings that are initiated on the poleward boundary of the auroral zone are not associated with substorms but, as pointed out by, e.g., *Lyons* [2000], are associated with the so-called "poleward boundary intensification (PBI)." To avoid this type of error, PBIs and small auroral brightenings associated with "pseudo-breakups" will be ignored in this study.

[15] The Polar UVI data are first corrected for background and flatness for the entire CCD. Then the processed image data are transformed from satellite perspective to a physically meaningful coordinate system such as geographic or geomagnetic coordinate system with correction to the nadir for a different viewing geometry. These processes reduce distortions in the auroral surface brightness and hence minimize misinterpretation of the data. Magnetic coordinates have been a nature coordinate system widely used for organizing high-latitude auroral activity, including the well-accepted auroral substorm morphology described by *Akasofu* [1964], because the aurora is a direct consequence of magnetosphere-ionosphere coupling. In the present study a magnetic coordinate system named the altitude-adjusted corrected geomagnetic (AACGM) coordinate system [*Baker and Wing*, 1989] is used. Other magnetic coordinate systems are also suitable and should produce subtle differences.

[16] Akasofu's classical auroral substorm is adopted in the present study [*Akasofu*, 1964]. After the UVI images are converted to AACGM, we examine auroral activity for signatures of auroral bulge/surge from a sequence of UVI images. Once a bulge is identified, we trace the bulge in the UVI images back in time to find the first intensification of the aurora associated with the subsequently expanded bulge, both poleward and azimuthally. This first auroral brightening is used as the auroral breakup. To distinguish between pseudo-breakup and auroral breakup, we also require that the subsequent poleward expansion of the brightened "arcs" must be no less than 1 degree in magnetic latitude.

[17] Based on the criteria mentioned above, possible substorm events are identified for the 43 shock intervals. Results are divided into three categories: potentially an SSC trigger (T), a false positive SSC trigger (F), and a quiescent event (Q). The result is given in the eighth column of Table 1. We will show one or two events in detail for each category in the following sections.

2.1. Potentially SSC Triggering Events

[18] Events belonging to this category reveal "potential" triggers of substorm expansion phase onset by shocks. To determine a triggered substorm, the time between an SSC and an onset must be defined. Previous studies have generally shown that substorms occur within 10 min of shock arrival [*Zhou and Tsurutani*, 2001]. In this study we require both negative magnetic bays and auroral breakups to be observed within a 20-min window starting at the time of shock arrival as indicated by an SSC/SI. This time window should be wide enough to include all possible triggered events. Furthermore, the strength of the magnetic bays, $|AL|$, must exceed 100 nT within 30 min of shock arrival. Based on these criteria four such events are identified (see sixth column in Table 1). One such event is illustrated in detail below.

2.1.1. 1 May 1997 Event

[19] One of the potentially triggered events occurred on 1 May 1997. The time-shifted solar wind pressure, the IMF B_y and B_z components, the auroral electrojet *AU* and *AL* indices, and the *Sym-H* index [*Iyemori*, 1990] are shown from top to bottom in Figure 1a. The *Sym-H* index measures the mean longitudinally symmetric component of the magnetic disturbances, averaged from six globally distributed magnetometers at middle latitudes, and is essentially the same as the hourly D_{st} index [*Sugiura*, 1964], except that the *Sym-H* index provides 1-min time resolution and is suitable for studies of high time variations of the ring currents. An SSC of moderate size ($\sim$30 nT) was registered by the *Sym-H* index at $\sim$1241 UT caused by an interplanetary shock, which was observed by Wind at $\sim$(215, -4.7, 23.5) R_E in GSM coordinates. Upstream of the shock the IMF B_z component was negative for more than 1 hour. Closer to the shock, the IMF started turning northward, with a noticeable fluctuation, while the IMF B_y stayed close to zero. Immediately downstream of the shock both the B_y and B_z components of the IMF slowly became negative and the westward auroral electrojet *AL* index started decreasing and reached -145 nT in $\sim$10 min.

[20] A sequence of 16 Northern Hemispheric auroral images from Polar UVI during the shock/SSC event is shown in Figure 1b. A clear auroral breakup took place at 67° MLAT and 2200 MLT at $\sim$1244 UT, $\sim$3 min after the arrival of the shock at the Earth's magnetosphere. This substorm occurred almost immediately after the SSC and may represent a good example of a substorm triggered by a shock. Of course, we are not sure whether or not the substorm was really triggered by the shock compression. Alternatively, it may be associated with the northward turning of the IMF in the shock upstream.

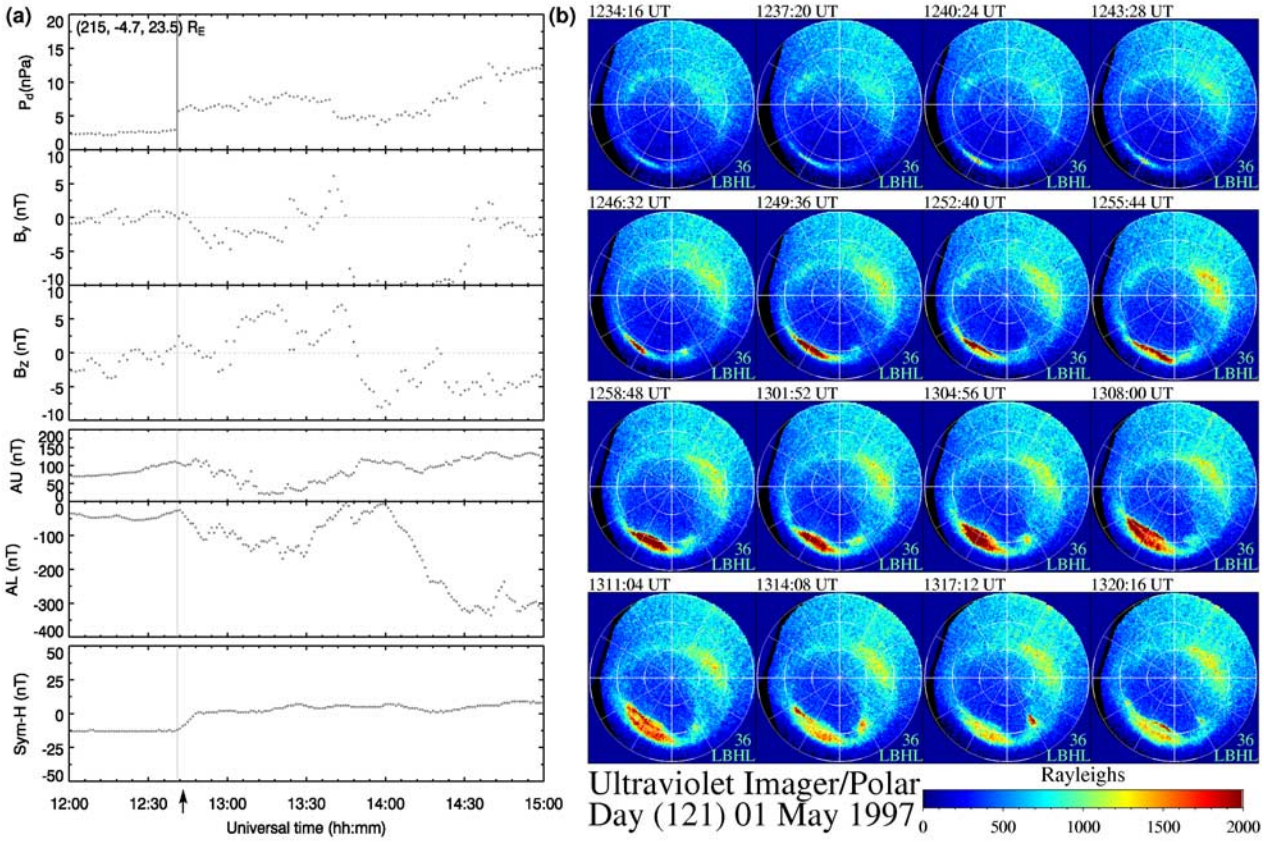

Figure 1. (a) Panels from top to bottom are the time-shifted solar wind pressure and IMF B_y and B_z components, auroral electrojet *AU* and *AL*indices, and the *Sym-H* index. An up-arrow marks the time of an auroral breakup (1243 UT) determined from the Polar UVI images. A light vertical line indicates the onset time of the SSC (1241 UT). (b) A sequence of auroral images in the N_2 Lyman-Birge-Hopfield (LBH) bands from the Polar ultraviolet imager during an interplanetary shock impact on the magnetosphere. The magnetic latitude (10° increments) and magnetic local time (2-hour increments; dusk at the bottom of each frame, and midnight to the right of each frame) are in Altitude Adjusted Corrected Geomagnetic Coordinates (AACGM) coordinates [*Baker and Wing*, 1989].

[21] Notice that a second magnetic bay with much larger strength occurred at ~1400 UT and was not accompanied by an auroral breakup (not shown). It was probably associated with a sharp southward turning of the IMF a few minutes earlier as an enhanced convection electric field driven by a continuously southward directed IMF can also enhance the auroral electrojets. This type of negative magnetic bay is called a "convection bay" and has been reported previously [e.g., *Nishida and Kokubun*, 1971; *Kawasaki and Akasofu*, 1973; *Kokubun et al.*, 1977].

2.2. False Positive SSC Triggering Events

[22] For this category of events we require a well-developed negative magnetic bay ($AL < -100$ nT) to be observed within a 30-min of window starting at an SSC/SI. However, no auroral breakup was observed in association with it. This type of event is usually associated with auroral intensification on the flanks of the oval and the poleward edge of the nightside oval. Two such events are shown below.

2.2.1. 31 January 1998 Event

[23] Figure 2a shows an event from 31 January 1998. An SSC of ~12 nT was registered by the *Sym-H* index at 1642 UT caused by an interplanetary shock, which was observed by Wind at ~(236, 12, 25) R_E in GSM coordinates at 1554 UT. The IMF was steadily southward ($B_z \sim -2.5$ nT) for several hours before the shock front. At the shock front, the IMF sharply turned northward, then fluctuated about zero for 20 min before it dropped to large negative values again. The steadily southward IMF did not produce a significant auroral electrojet before the arrival of the shock. About 4 min after the shock arrival, the westward auroral electrojet intensified ($AL \sim -150$ nT) and lasted for ~40 min. This negative excursion of the *AL* index (negative magnetic bay) is typical of the substorm expansion phase. Therefore from the ground magnetometer data, interpreting this as an SSC triggered substorm event seems to be justified.

[24] Figure 2b shows a sequence of 16 Northern Hemispheric auroral images in AACGM coordinates from Polar UVI during the SSC event. According to the *AL* index, one would expect a small auroral breakup a few minutes after the SSC onset. It is surprising, however, that no auroral breakup occurred in association with the negative bay by shock impingement until ~1747 UT (not shown). We do not consider the late occurring auroral breakup as being triggered by the shock, because the two phenomena were

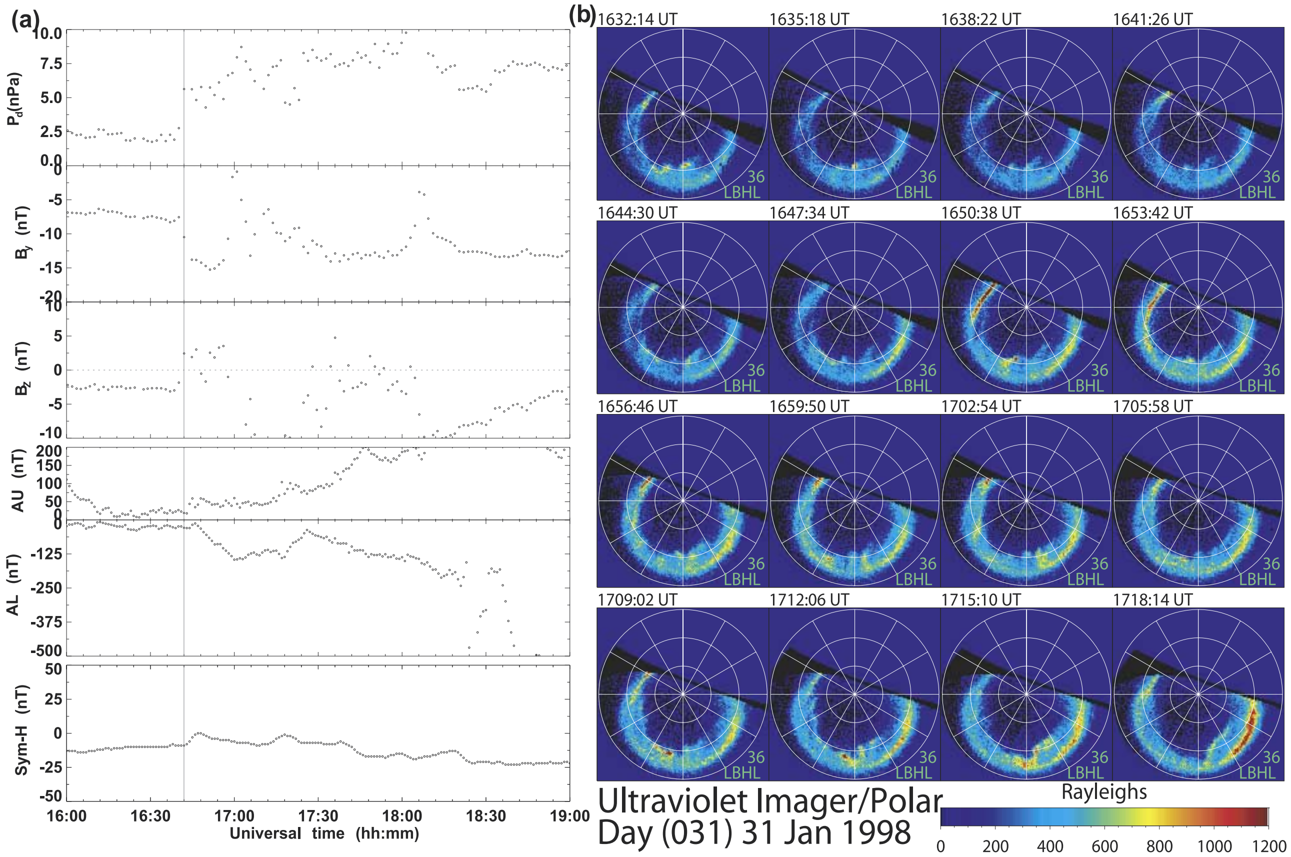

Figure 2. Same format as Figure 1 for 31 January 1998. The SSC time is 1642 UT.

separated by more than 1 hour. A few minutes after the shock impact, there are two major auroral brightenings: one on the poleward edge of the premidnight oval and one on the equatorward edge of the postmidnight oval. However, the oval auroral luminosity is weak and may have caused the small negative bay.

[25] During this event a low-latitude magnetometer from Kakioka, which was located in the midnight sector (LT = UT + 9), did not detect any Pi2 pulsations (see Figure 3). In addition, the LANL 1994-084 satellite, which was located at the premidnight sector during the passage of the shock, found no evidence of substorm injections either. These observations indicate no evidence of substorm association with the SSC. This event clearly demonstrates that an SSC/SI-associated magnetic bay need not be accompanied by an auroral breakup, even though the IMF was negative for many hours upstream of the shock.

2.2.2. 8 May 1998 Event

[26] This event is selected mainly because it was associated with a large, sharp negative bay of typical substorm time scale. A clear SI was registered by the *Sym-H* index at 0951 UT caused by an interplanetary shock, which was observed by Wind at ~(211, 7, 30) R_E in GSM coordinates at ~0923 UT (see Figure 4a). Three minutes later, the westward auroral electrojet sharply decreased by over 350 nT. This was a clear negative magnetic bay event, and was probably triggered by the IP shock. Note that *AE* (= *AL-AU*) was ~200 nT before the negative bay onset, a preferred condition for the triggering of magnetic bays [*Kokubun et al.*, 1977].

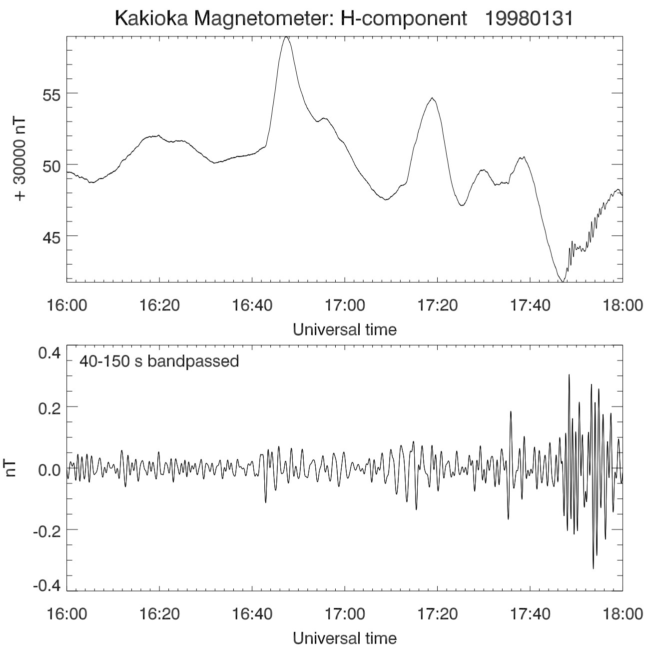

Figure 3. The original (a) *H* component and (b) band-pass (40–150 s) filtered *H*-component geomagnetic field variations from the Kakioka station for an interplanetary shock event on 31 January 1998.

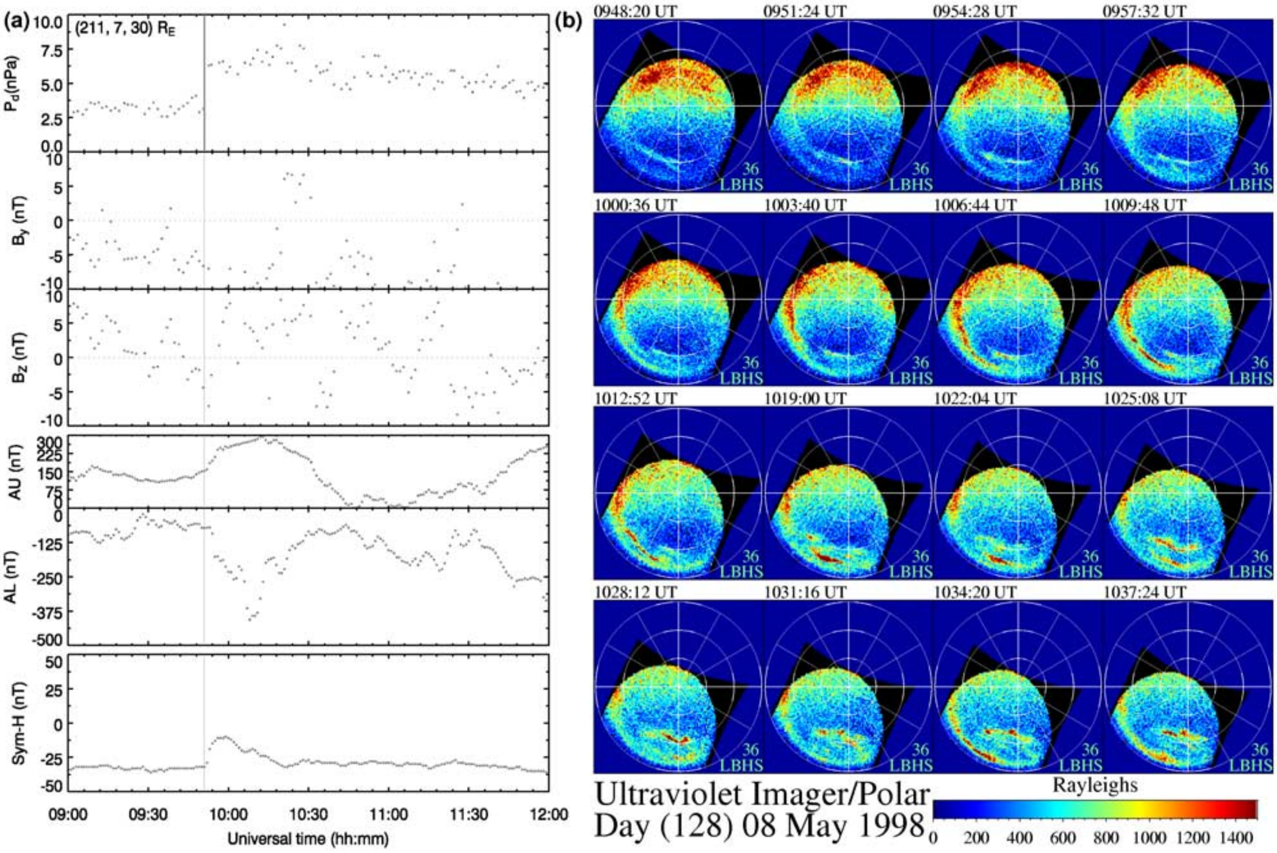

Figure 4. Same format as Figure 1 for 8 May 1998. The time for SSC is 0951 UT

[27] According to a sequence of auroral images from UVI during the SSC interval (Figure 4b), there was no classical auroral substorm as described by *Akasofu* [1964]. The auroral display from UVI revealed a couple of thin brightened "arcs" of ~100–200 km in latitudinal width. Immediately after the SSC the aurora luminosity intensified on the duskside of the oval (the dawnside oval was not covered by UVI during this time) and appeared to extend toward the nightside. A second prominent arc on the poleward edge of the oval intensified ~12 min after the shock impact and drifted poleward and eastward. A westward current system associated with this auroral form might have caused the negative bay to be observed on the ground. The impact and passage of the high-pressure shock simply enhanced existing auroral structures. Notice that the small brightening on the poleward edge of the double oval before and after the SI may have been associated with an auroral poleward boundary intensification (PBI) [*Lyons*, 2000].

[28] For this particular event GOES 9 was located at midnight at the time of the shock impact. The three components of GOES 9 magnetometer data in GSM coordinates show an increase in the x-component and a decrease in the *z*-component of the magnetic field during the shock passage (see Figure 5). This indicates that the shock compression did not lead to dipolarization but rather stretching of the magnetotail field (tail inflation) and is consistent with compressed lobe fields by high solar wind dynamic pressure downstream of the shock.

[29] Before leaving this section, one should point out that an imprecisely timed onset from magnetograms can also lead to the interpretation of this type of events. Sometimes an auroral breakup occurred several minutes before the occurrence of an SSC/SI. However, these small time differences cannot be easily distinguished by a magnetic bay. As

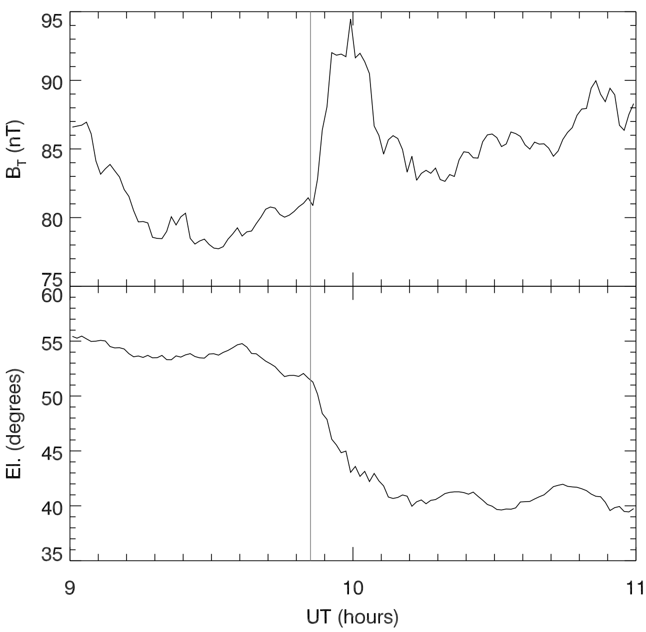

Figure 5. Three components of magnetometer data in GSM from GOES 9 for 8 May 1998, indicating anti-dipolarization of the magnetotail at SSC (vertical line).

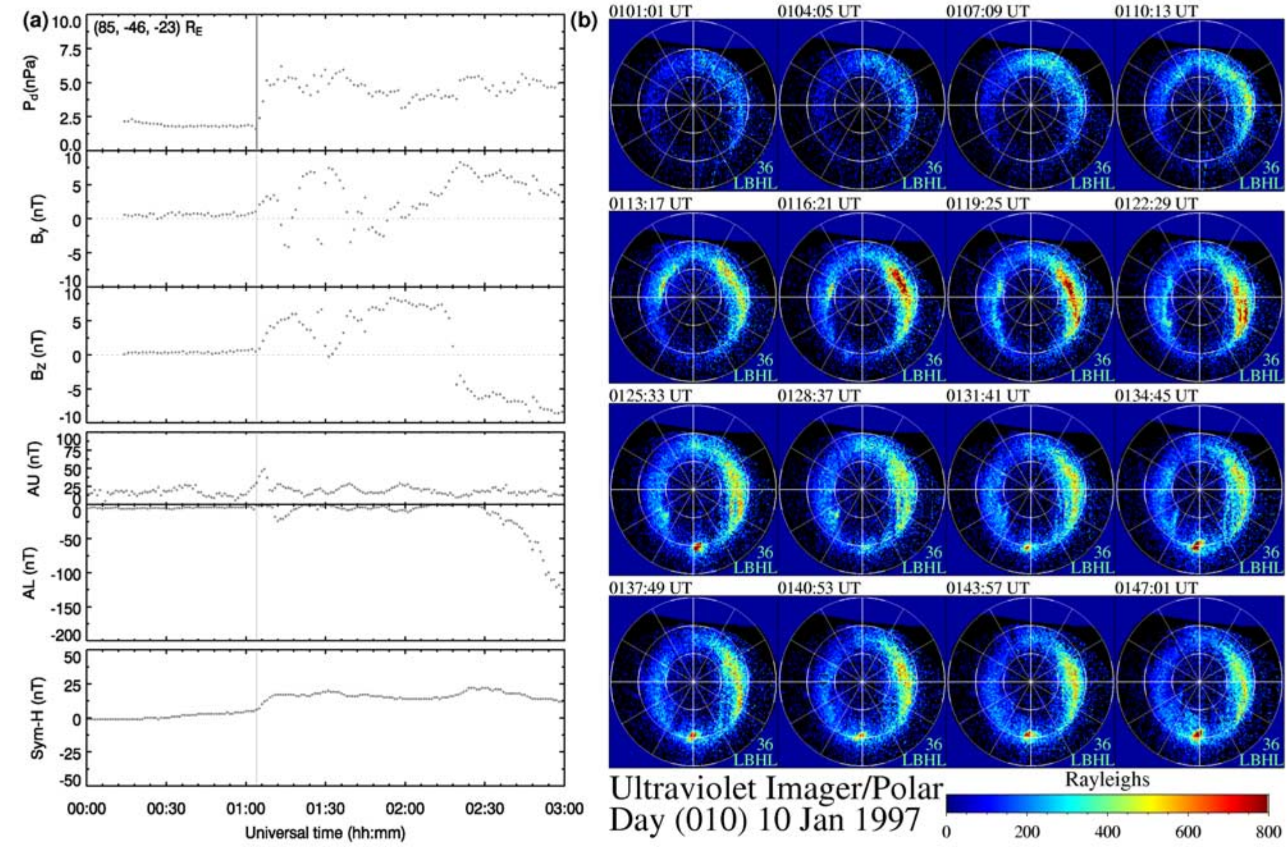

Figure 6. Same format as Figure 1 for 10 January 1997. The time for the SSC is 0104 UT.

a consequence, the onset may be misidentified as triggered by the SSC/SI. Two such events were found on 3 May 1998 and 3 August 1997 (not shown). This type of event is also considered as the false positive category.

2.3. Quiescent Events

[30] A large number of the events studied appeared to have no indication of both negative magnetic bays and auroral breakups. That is to say that most IP shocks did not produce significant disturbances in the form of particle precipitation and currents. These quiescent events are associated with a positive IMF B_z. A detail statistical study will be given in the next section. Since most of the events of this category reveal similar auroral displays, we will only show one event here.

2.3.1. 10 January 1997 Event

[31] This is a well-studied 10 January 1997 magnetic cloud event (Figure 6a) [e.g., *Burlaga et al.,* 1998]. During this event the Wind spacecraft was located in the solar wind at $\sim$(85, -46, -23) R_E in GSM coordinates and observed an IP shock at 0052 UT. The 1-min IMF B_z component was small (<1 nT) but stable for $\sim$1 hour. An SSC was recorded 12 min later on the ground at 0104 UT. The *AL* index was slightly increased ($\sim$25 nT) and lasted a few minutes. At the shock front the IMF B_z component sharply turned northward and stayed mostly positive. By 0218 UT, the IMF turned sharply southward and initiated the main phase of the storm. The westward electrojet (*AL*) was enhanced at the same time.

[32] A sequence of 16 Polar UVI images shown Figure 6b indicate that after the shock impact on the magnetosphere the first aurora brightening occurred on the dayside. The brightening seemed to propagate toward the night sector first from the dawn and then from the dusk oval. About 20 min later, at 0125 UT, a small brightening, probably associated with a pseudo-breakup, occurred at midnight but did not develop into a full-scale substorm level [*Spann et al.*, 1998]. The shock induced brightened auroral regions did not extend to and close at midnight, forming a midnight gap of $\sim$3–4 hours wide in MLT. We have noticed that the westward electrojet (*AL*) started to enhance at 0230 UT right after the southward turning of the IMF. One could consider this decrease in *AL* as a substorm. Interestingly, this negative bay is not associated with an auroral breakup. Actually, the size of the polar cap started to increase after 0230 UT in response to the sharp southward turning of the IMF at 0220 UT, and *Germany et al.* [1998] interpreted this time period as the growth phase of a substorm that commenced at 0343 UT.

2.4. Statistical Results: IP Shocks

[33] We have examined the Polar UVI image and other data for all 43 events individually and the results are listed in Table 2. Negative magnetic bays with $AL < -100$ nT occurring within 30 min of SSCs were identified in 22 (52%) events. Minimum values of *AL* for each of the 43 events are given in the fifth column of Table 1. However, there are only four (9%) auroral breakups identified within

Table 2. Summary of Statistical Results: IP Shocks

Event Types	Number of Events	Percentage
SSCs/SIs	103	
Concurrent UVI	53	
Associated with IP shocks	43	
Negative magnetic bays	22	52%
Auroral breakups	4	9%

20 min after the SSCs and 2 (5%) within 10 min after the SSCs.

[34] Although there is a 50% of chance that an impingement of a shock can lead to a negative magnetic bay with $AL < -100$ nT, only 1/5 of those bays are associated with auroral breakups. It is useful to investigate IMF conditions for these shock events to sort out conditions that can lead to a breakup. Specifically, we will examine the IMF B_z component. The average value of the IMF B_z within a 30-min window before and after the shock for each event is determined. Events are classified based on the sign (an "N" for negative and a "P" for positive) of the IMF B_z component: B_z was negative both upstream and downstream of the shock (NN), B_z was negative upstream of the shock but became positive downstream of the shock (NP), B_z was positive both upstream and downstream of the shock (PP), and B_z was positive upstream of the shock but became negative downstream of the shock (PN). The result is listed in the seventh column of Table 1 and the summary is given in Table 3 and Figure 7. As expected, a northward IMF component dominates the quiescent ($AL > -100$ nT) events, while a southward IMF component dominates the active ($AL < -100$ nT) events. Quantitatively, the average (median) IMF B_z was 1.9 (1.5) nT upstream and 3.4 (3.7) nT downstream the shock for quiescent events, while the average (median) IMF B_z was -1.8 (-1) nT upstream and -2.4 (-1) nT downstream the shock for active events.

[35] The correlation coefficient between AL and the 30 min averaged IMF B_z is poor, 0.30 for the upstream and 0.12 for the downstream. A primarily southward IMF both upstream and downstream of the shock (i.e., NN type) seems to be a preferred condition for triggering a breakup. However, the majority of the NN events are not associated with a substorm.

2.5. An Alternative Trigger: IMF

[36] One of the most difficult tasks in associating geospace phenomena with disturbances in the solar wind plasma and magnetic field is propagating the solar wind from a single point measurement to Earth. This has been a major source of controversy in evaluating substorm triggering mechanisms. It is well known that there is a good one-to-one correspondence between IP shocks and SSCs/SIs. As a result, the onset time of an SSC/SI can be used as the arrival time of a corresponding shock at the magnetopause. If a substorm occurs around an SSC/SI, the IMF can be timed precisely by shifting the time axis by the time difference between the SSC/SI and the substorm onset, assuming that the spatial structure of the IMF does not vary much in time. This criterion limits us to substorms during SSC/SI periods. To eliminate the complexity of multiple onsets, we will focus only on isolated substorms. Based on these criteria, a total of 11 auroral breakups are identified to occur within 1 hour of the SSCs, with five events occurring after and six events occurring before the SSCs. The z and y components of the IMF measured by Wind for these events are plotted in Figure 8 as solid lines. The date and location of the Wind in GSM at the time of breakup is provided at the upper left corner of each panel. Crosses plotted in some panels are data taken either from observations from Geotail or IMP8 spacecraft, which are closer to the Earth than is the Wind and hence provide more reliable IMF data. Figure 8a reveals two common IMF B_z features prior to onset: (1) the IMF was either entirely or partially negative in the 1 hour period prior to the onset and (2) the majority (55%) of onsets occurred during a positive excursion of the IMF B_z component. These gross features can also be seen from the bottom panel of the Figure 8a, which shows the superposed IMF B_z component from the 11 events. The average IMF turned southward approximately 1 hour prior to the onset. This suggests that a typical one hour enhanced energy coupling between the solar wind and the magnetosphere is a necessary condition for producing an isolated substorm.

[37] It is also shown in a number of events that a reduction in the magnitude of IMF B_y to near zero seems to have triggered substorms [*Troshichev et al.*, 1986]. We have also plotted IMF B_y for the 11 substorms in Figure 8b. By examining the 11 events one by one, there are no systematically identifiable changes in B_y 30 min prior to the each onset. Three events are associated with a stable IMF B_y (960728, 980503, and 990310), five events are associated with an increase in the magnitude of IMF B_y (970622, 971106, 971122, 980924, and 981113), and only four events are associated with a decrease in IMF $|B_y|$ (970209, 970501, 970803, and 971106). A cross examination of B_z and B_y shows that the three of the four $|B_y|$ reduction events are associated with northward turnings of the IMF and one associated with a stable B_z. The combined result indicates that seven substorms (64%) may have been triggered by the convection reduction mechanism [*Lyons*, 1995]. A summary of this section's results is given in Table 4.

3. Discussion

3.1. Solar Wind Plasma Discontinuities

[38] We have studied a total of 43 SSCs/SIs events caused by interplanetary shocks and found that 52% of the events were followed by a magnetic bay ($AL < -100$ nT) within a 30-min window starting at the SSC/SI. Statistically, this is consistent with the 43% reported by *Kokubun et al.* [1977]. Recently, *Zhou and Tsurutani* [2001] analyzed auroral displays with Polar UVI images and the westward electrojet AL index during 18 IP shock events, and they reached a similar conclusion that 44% of events were followed by substorm expansion phase onsets. However, there is an apparent discrepancy between *Zhou and Tsurutani* [2001] and the

Table 3. IMF Type for Each Type of Shock Event

Event Types	NN	NP	PN	PP
Quiescent ($AL > -100$ nT)	3	2	2	12
Active ($AL < -100$ nT)	11	4	4	3
Breakup	3	1		

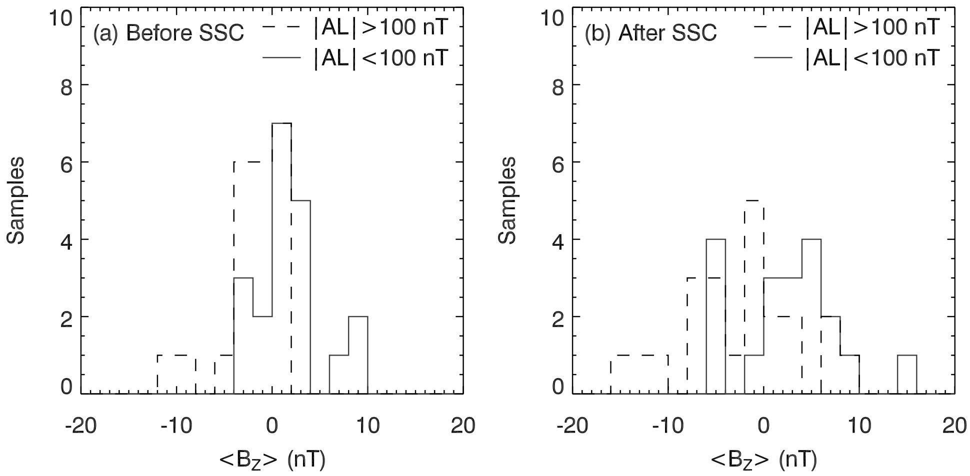

Figure 7. Distributions of the shock events in terms of the mean IMF B_z component both (a) upstream and (b) downstream of the shocks.

present study result. The majority of the magnetic bays found in this study were not accompanied with auroral breakups. In other words, these magnetic bays are not substorms.

[39] What differentiates *Zhou and Tsurutani* [2001] results from ours lies in the interpretation of the auroral image data. They considered all auroral intensifications as substorms, but we do not. Statistically, auroral d*P*/d*t* cannot be used to identify substorms [*Newell et al.*, 2003]. The substorm is a chain of physical processes taking place in the nightside sector of the magnetosphere-ionosphere system, which lead to the phenomenon of the auroral substorm described by *Akasofu* [1964]. It is conceivable that some magnetospheric processes other than substorms can also result in auroral activity. The shock event of 24 September 1998, shown in Plate 1 of *Zhou and Tsurutani* [2001] is a good example to demonstrate our view. They assumed that the shock impingement at 2344 UT triggered a substorm ~4 min later, as seen from the large increase in the auroral luminosity in the premidnight sector. However, we believe that the real onset of the substorm event took place at ~2145 MLT and 60° MLAT at 2312 UT. The *AE* stations did not detect the substorm disturbance because of the unusual low latitude and local time of the substorm. However, a large negative bay of ~350 nT was seen, first by one of the IMAGE magnetometer network station, OUJ (MLAT = 61°), and later by other higher-latitude stations with smaller magnitudes. At the geosynchronous orbit, the GOES 8 satellite, which was located at ~1900 LT, did not detect magnetic field dipolarization at and after the time of the SSC. In addition, near-dispersionless energetic electron injections was observed at LANL 97A, which was located at ~0206 MLT, at 2120 UT (not shown). Magnetic field and energetic particle observations from geosynchronous satellites do not show any substorm features at and after the SSC either. Therefore magnetospheric compression by the shocks simply enhanced the ongoing substorm events. Actually, many of our events, including the events (Figures 2 and 4) shown in the previous section, do reveal some forms of auroral intensification in the nightside sector a few minutes after the shock arrival. These auroral brightenings do not have typical auroral breakup and auroral bulge signatures; however, they are associated with enhanced westward electrojets (i.e., magnetic bays).

[40] Previous studies have generally concluded that an SSC/SI is followed by a substorm under some conditions, such as a large *AE* (*AE* > 100 nT) [*Kokubun et al.*, 1977] and a negative IMF B_z 30 min prior to the SSC [*Burch*, 1972]. The study of *Zhou and Tsurutani* [2001] also concluded that a preconditioned magnetosphere, e.g., by a southward IMF for about 1.5 hours, is a necessary condition for a substorm to be triggered by a shock. These conditions are basically equivalent and indicate that a preconditioned magnetosphere is a necessary condition for the triggering of a substorm expansion onset by the impact of an interplanetary shock. Note that all these criteria were derived based mainly on magnetic bays. Indeed, many of our events apparently satisfy this criterion (for example, see Figure 2), and magnetic bays were also observed, but most of these magnetic bays are not substorms. Although a southward IMF component prior to the shock is a preferred condition that leads to the formation of a magnetic bay, the strength of the bay correlates poorly with the IMF B_z component, indicating other responsible mechanisms.

[41] Compression of the magnetosphere by a shock can lead to a negative magnetic bay, not specifically associated with a substorm. Since this type of bay is directly related to shock compression, we may call it a "compression bay," in some sense analogous to a convection bay. In other words, negative magnetic bays appeared in the auroral zone are not unique to the substorm process. This certainly casts doubts on studies that used magnetic bays as a sole substorm proxy. Interplanetary shocks usually associated with coronal mass ejections, a major source of geomagnetic storms. Auroral electrojet indices has been widely used in studies of storm-substorm relationships. Therefore cautions must be taken when interpreting results from such studies. Another issue not addressed in this study but important to the magnetospheric physics is whether other types of solar wind plasma variations can also have similar effects on the auroral electrojets. If they do, how do they affect the electrojets and can the effect be separated from that caused by a southward IMF component? These questions will be addressed in a future paper.

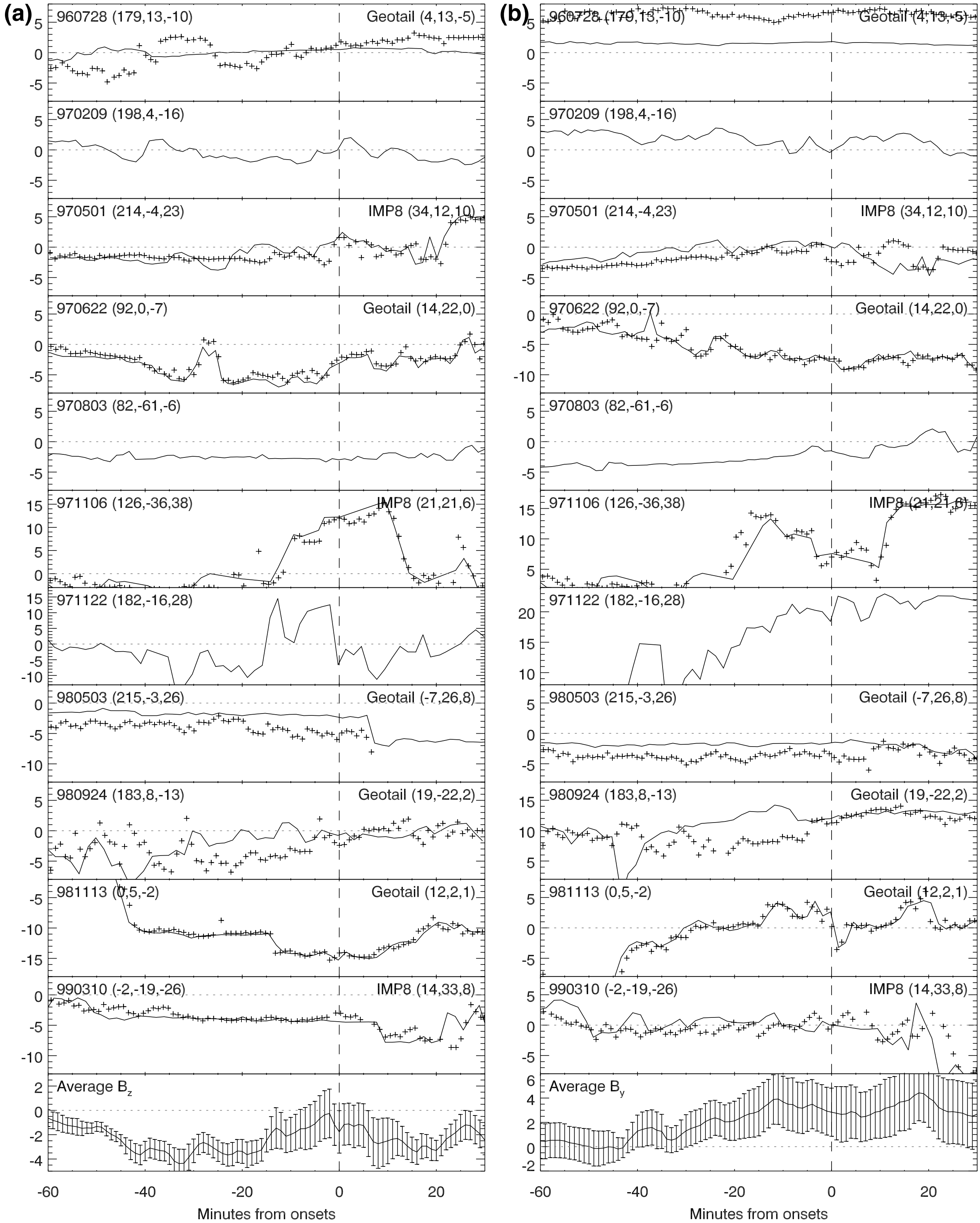

Figure 8. Propagated IMF B_z (a) and Bz (b) components 60 min before and 30 min after auroral breakup for the 11 events. The zero time corresponds to the auroral breakup time. The solid line plotted in each panel is taken from the Wind data. Crosses plotted in some panels are data either from Geotail or IMP8 spacecraft as indicated by the legends at the upper right corner of the corresponding panel. The bottom panels are the average value of each component derived from a superposed epoch analysis. The error bars show one standard deviation of the sample mean.

Table 4. Summary of Statistical Results: IMF

Trigger Types	Number of Events	Percentage	Events, YYMMDD
Northward turning	6	55%	960728, 970209[a], 970501[a] 970622, 971106[a], 980924
Southward turning	1	9%	971122
Reduction in $\|B_y\|$	4	36%	970209[a], 970501[a], 970803 971106[a]
B_y polarity change	1	9%	981113
Stable IMF	2	18%	980503, 990310

[a]Associated with a northward IMF turning and a $|B_y|$ reduction.

[42] It is not clear at this point how the shock can enhance an auroral electrojet. Apparently shock-induced auroral precipitation should enhance the ionospheric conductivity and enhance the auroral electrojets. Whether the enhanced ionospheric conductivity alone can account for the enhanced auroral electrojets is not known and deserves further studies. The cause of enhanced auroral electrojets is not directly related to enhanced convection becasue of a poor correlation between the southward component of IMF and *AL*. However, the effectiveness of a pressure jump in producing a magnetic bay seems to depend on the southward IMF prior and/or subsequent to the shock front. A northward IMF generally results in a weaker *AE*. When coupled with a northward IMF, the enhancement from shock compression is very limited, because this type of auroral precipitation is usually small (see, e.g., Figure 6). On the other hand, when the IMF is negative, the impingement of shocks can produce large compression bays (see, e.g., Figures 2 and 4). It is shown recently that auroral electrojets are well correlated linearly with solar wind density [*Shue and Kamide*, 2001]. From the two density pulse events they studied, one during a steady southward and the other during a steady northward IMF, it is shown that the density effect is dominant in the westward electrojet for IMF $B_z < 0$ and in the eastward electrojet for IMF $B_z > 0$. Therefore the compression by a shock may act as a catalyst that facilitates releasing the previously stored energy from the magnetosphere.

[43] Intensification of auroral luminosities associated with shock compression of the magnetosphere is commonly found in the present study. There are several auroral forms that have also been reported in association with the shock compression [e.g., *Zhou and Tsurutani*, 1999; *Liou et al.*, 2002b]. The region of intensification seems to magnetically map to the region of compressed magnetosphere. At the midday sector, where an IP shock usually makes the first contact with the magnetosphere, transient auroral patches of a few hours MLT wide in local time may appear at latitudes below the typical oval [*Liou et al.*, 2002b]. The midday auroral patches (MSPs) occur simultaneously (within 1 min) with respect to the onset of SSCs. Auroras in the main oval also intensifies. A sudden brightening of aurora first appears in the day sector, but not necessarily at noon. The region of auroral intensification then ''propagated/extended'' to the nightside along the dawn and dusk oval with a typical time scale of 10–20 min [*Zhou and Tsurutani*, 1999]. In the night sector, auroral brightening at the polarward edge of the oval and/or intensification of previously activated auroras are common, and they are likely to be associated with auroral poleward boundary intensifications (PBIs) [e.g., *de la Beaujardière et al.*, 1994; *Lyons et al.*, 1999; *Zesta et al.*, 2000]. Some event studies have connected PBIs with enhanced bursty magnetic reconnection in the magnetotail [*de la Beaujardière et al.*, 1994]. Therefore our results seem to suggest, though indirectly, that magnetosphere compression can enhance tail reconnection. In contrast to substorms, which are associated with reconnection in the midtail region, this pressure enhanced reconnection takes place in the distance tail.

3.2. IMF Variations

[44] We have studied 11 substorm events that occurred within a 1-hour time window centered at the SSC/SI such that IMF can be timed fairly reliably. This method, however, does not take into account the fact that the IMF structure is so complex and dynamically changing that the true IMF that makes contact with the magnetopause does not necessarily the same as that measured at other places in space. This problem cannot be easily resolved by single satellite measurement unless the satellite is located in front of the subsolar magnetopause.

[45] Based on more reliable substorm indicators and timed IMF data than previous studies, it is found that 7 out of 11 substorm expansion phase onsets can be associated with either northward turnings of the IMF or reductions in IMF $|B_y|$ or both. This is consistent with recent study results from *Lyons et al.* [1997] and *Blanchard et al.* [2000], although their studies are subject to large uncertainties from improperly timed IMF. It is worth mentioning that these onsets are typically preceded by a negative IMF B_z that lasted ~1 hour. Superposed epoch analysis from early studies also shows the requirement of the southward IMF during the substorm growth phase [*Caan et al.*, 1977; *Samson and Yeung*, 1986]. This 1 hour period of southward IMF before onset is also consistent with recent work of *Newell et al.* [2001], who analyzed hundreds of substorm events determined from global auroral images from Polar UVI and carefully propagated IMP-8 IMF data. They found a declining B_z that started ~1 hour prior to onset. However, their superposed epoch analysis did not show evidence of substorm onset triggered by either northward or azimuthal turnings of IMF. It is not obvious why the discrepancy exists, since both studies used auroral breakups as an onset indicator. The difference may stem from the way the IMF data were analyzed in the two studies. We suspect that uncertainties in their IMF timing could be at least on the order of 10–20 min [*Ridley*, 2000], which may smooth out the highly variable IMF B_z when averaged over a large number of events.

4. Summary and Conclusions

[46] In this report we examined auroral displays and magnetic field signatures during 43 SSC/SI events, all associated with interplanetary shocks, occurring between 1996 and 1999, to test the mechanism of compressional triggering of substorm expansion phase onset. It is found that ~52% of the surveyed shocks produced negative magnetic bays with $AL < -100$ nT. Statistically, this is consistent with previous results [e.g. *Kokubun et al. 1977*]. However, only four (<10%) of these magnetic bays were found to be associated with auroral breakups. This evidence of a low probability of observing substorm onsets after

SSCs/SIs suggests that interplanetary shocks do not trigger substorm expansion onsets. On the other hand, the occurrence of a substorm is more likely to be associated with a northward turning of the IMF. At least one half of 11 substorms studied reveal this possibility.

[47] One important finding is that negative magnetic bays are not always associated with substorms. A poor correlation between the *z*-component of the IMF and the strength of the bays indicates other mechanims than magnetic field merging responsible for the cause of the negative magnetic bays. Although the direct cause of negative bays is not yet clear, some are definitely associated with compression of the magnetosphere by shocks. The finding that negative magnetic bays are not unique to substorms certainly casts doubts about many previous substorm-related studies based on high-latitude magnetometer data.

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